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OPTIMIZATION IN THE SYSTEMS ENGINEERING PROCESS

Loren A. Lemmerman

The essential elements of the design process consist of the mission definition phase that provides the system requirements, the conceptual design, the preliminary design and finally the detailed design (Figure 1). Mission definition is performed largely by operations analysts in conjunction with the customer. The result of their study is handed off to the systems engineers for documentation as the systems requirements. The document that provides these requirements is the basis for the further design work of the design engineers at the Lockheed-Georgia Company.

The design phase actually begins with conceptual design, which is generally conducted by a small group of engineers using multidisciplinary design programs. Because of the complexity of the design problem, the analyses are relatively simple and generally dependent on parametric analyses of the configuration. The result of this phase is a baseline configuration from which preliminary design may be initiated.

Preliminary design is far more complicated, both because the analysis techniques are more complex, and also because these techniques require specialized knowledge. The objective of this step is to refine the design estimates made during conceptual design and to add additional detail to the description of the configuration. At the conclusion of this phase, the aircraft is defined well enough so that a company can comfortably bid the cost of producing it.

Detail design is largely mechanical in nature, and normally occurs after receipt of an order for production. This is not an area of concentration in this presentation, however.

To provide a basis for amplification of the conceptual design process, look at Figure 2. The function of the conceptual design process is to conduct a multidisciplinary analysis of an aircraft to produce values of parameters that describe an aircraft. These parameters are top level descriptions that leave most of the actual configuration details undefined.

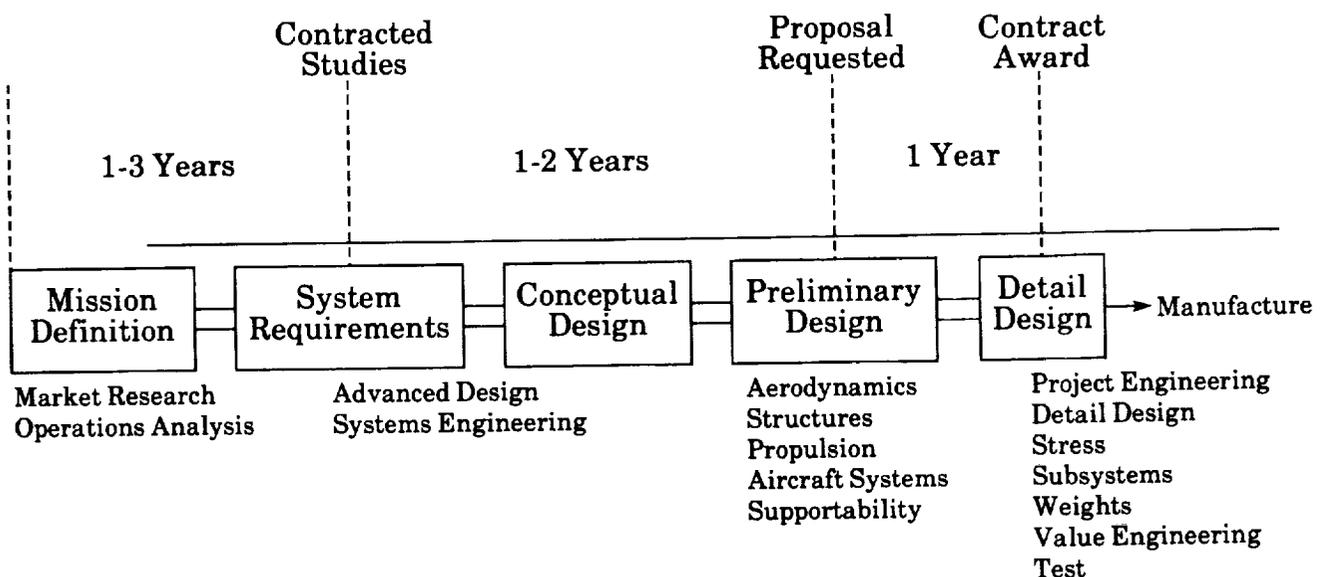


Figure 1 Essential Elements of the Design Process

However, implicit in this process is the trading of factors that relate to the performance of the configuration. The trades I mean are typified by the thinness of a wing desired by an aerodynamicist versus the thickness of a wing as desired by a structural analyst.

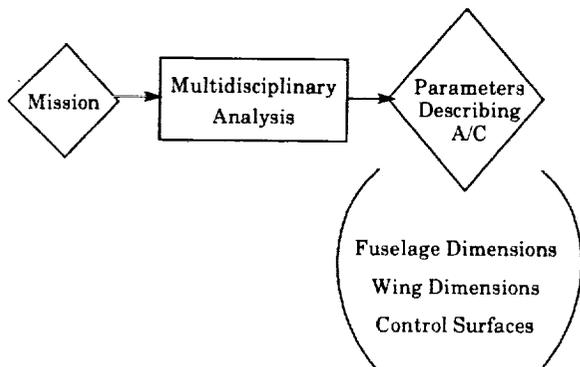


Figure 2 Conceptual Design

Typical parameters defined at this stage are fuselage length and width, wing area, sweep, aspect ratio and, to a limited extent, control surface.

In former times, conceptual design was manually directed and highly iterative. The process consisted of guessing an initial configuration, analyzing that configuration, and then systematically varying each of several design parameters to examine a design space within which manual optimization could take place. Normally the number of parameters examined did not exceed four, because of the human limitations in absorbing more variations than that. There were several disadvantages to the former approach. This process was time consuming, fallible and tedious. It was time consuming because the answer depended on many executions of a computer code. It was fallible because the choice of the parameter variation to be examined was entirely at the discretion of the designer. Thus, the quality of the answers was directly dependent on the skill of that designer. In addition, no one could be sure that a large enough design space had been

investigated to ensure that a true optimum had been found. This old procedure was also tedious. All data had to be manipulated manually. Although this did provide useful insight to the designer, the cost was a further delay. Dozens of computer runs had to be scanned, the results judged for correctness, and the results plotted on carpet plots. Many hours of talented labor were consumed performing menial tasks.

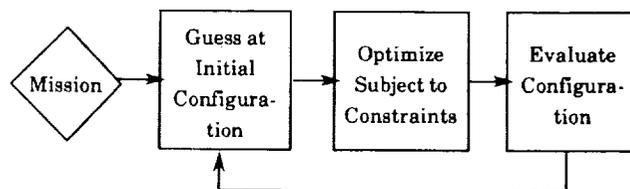


Figure 3 Preliminary Design

The former process was basically eliminated at Lockheed-Georgia several years ago, in favor of the approach shown here, based entirely on numerical optimization. The new process is described schematically here (Figure 3). The former process was usually completed in one day. Many of the manual actions have been eliminated. Now, a given study may consume as much time as formerly, but a much larger range of design variables has been included.

PRELIMINARY DESIGN PROCESS (PARTIAL)

The next step in the design process is preliminary design. This is the process, partially illustrated in Figure 4, by which the conceptual design baseline is analyzed in greater depth to confirm the design or provide foundation for changing the design. This process is typified by the more or less simultaneous execution of many detailed design codes in several disciplines. Obviously, the communication during the process is difficult, and the designs proposed by each discipline are frequently inconsistent. Iterative loops, while very common, cannot be represented because

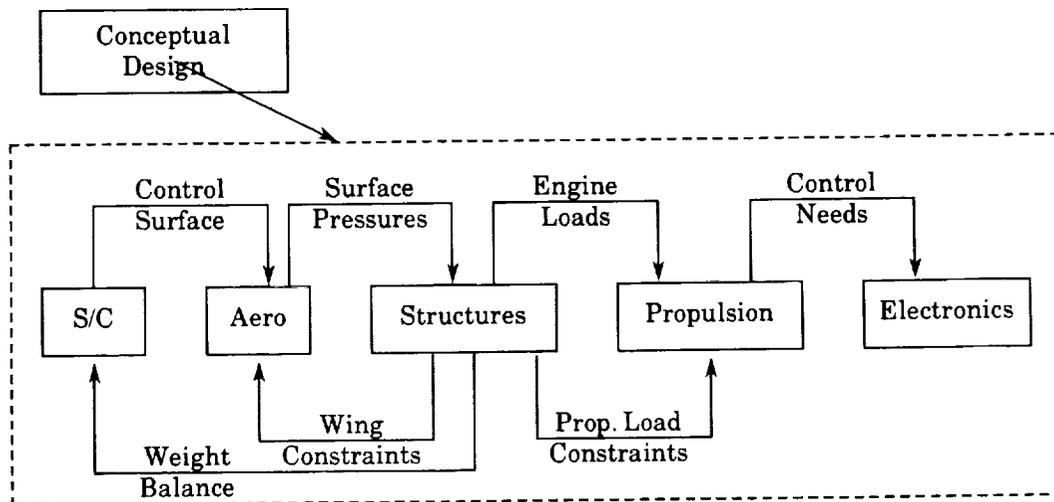


Figure 4 Preliminary Design Process

of the indeterminate sequence of such iteration.

As an example of the type of analysis conducted in this phase, consider aerodynamics for a moment. The codes frequently applied in this phase consist of full potential subsonic or transonic codes for configuration analysis, full potential codes for direct design, and Navier-Stokes codes for highly complex viscous flow analyses. As a result of the aerodynamic analysis done during this phase of design, the wing external contours are fully defined and more reliable estimates of the vehicle performance are available. Similar refinements and definition are added by each of the participating disciplines.

The deficiencies of the current approach are immediately obvious. First and foremost, the result is a suboptimal configuration. Even though optimization may be used within isolated analyses, the difficulty of communication in real-time and the lack of available tradeoff criteria mean that no global, rigorous optimization occurs.

I have already alluded to the use of optimization on individual analyses in this phase. Here are some examples of such optimizations. The aerodynamics discipline has been very active in developing optimization techniques for the design of wings in transonic flow, largely based on FLO codes. These

methods provide a wing shape, starting with a specification of a desirable pressure distribution. Using such methods, the wing contour and twist distribution may be calculated directly.

Subsonic optimization techniques have generally been limited to the design of high lift systems. In this case, the optimal location of a slotted trailing edge flap can be found by optimizing on the axial force for the system and by using paneling methods for calculating the flap system pressure distribution.

Structural optimization has been done for minimizing structural weight, given loading conditions. In this case, the structure is modeled using finite element techniques, with element geometries such as thicknesses or cross sectional areas taken as design variables. Another example of structural optimization is in the design of composite panels. The objective is to determine the ply orientation to respond to specific loading conditions.

If I were to summarize the preliminary design optimization work currently being done at Lockheed-Georgia, I would have to say that its use is relatively new, that it has been very well accepted, and that its use is certainly increasing. But this may eventually become a severe problem for us, since the optimization is being applied to subprocesses within design. Worse yet, it is being applied

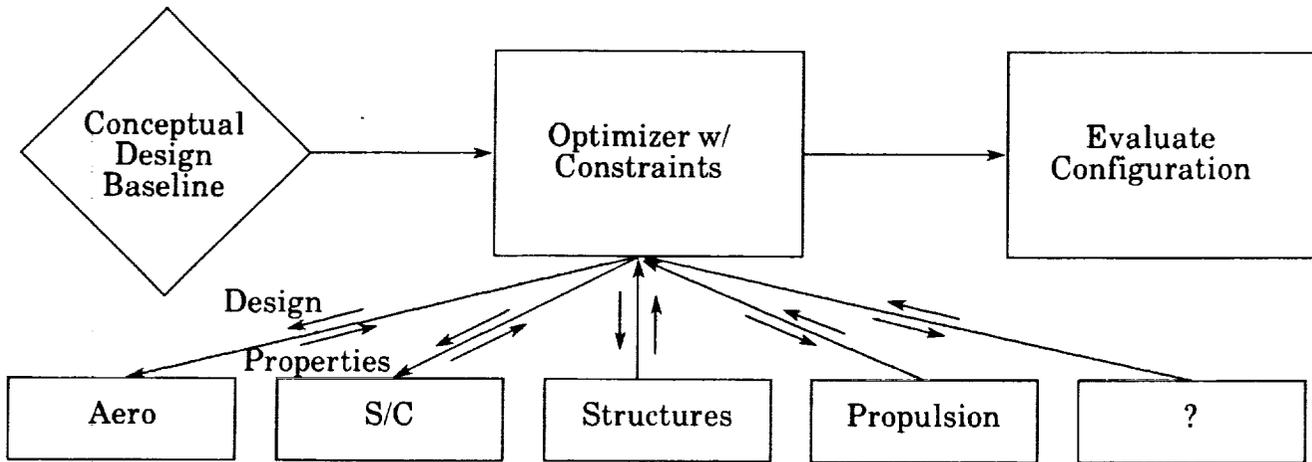


Figure 5 Proposed Preliminary Design Process

to old design philosophies. The result has to be suboptimal designs.

The preliminary design process is clearly another candidate for improvement by optimization. The technical challenge of this problem is much greater than that of the conceptual design process, but the potential payoff is also much larger. The challenge comes, in part, from the large number of individuals and computer programs normally invoked at this design state, and the current dearth of technology available to solve the very different problems thus posed.

One possible way to apply optimization in the preliminary design process is shown here. The fundamental idea is that candidate design parameters flow downward to the individual analysis modules and the result of the analysis flows back up to the optimizer.

Obviously, such a system is far from reality. The technical challenges outweigh those of optimization itself. The analysis methods normally used in preliminary design are state-of-the-art methods that are time consuming, user-sensitive and modeling sensitive. Because of this, not only will new optimization techniques be needed, but so will entirely new operational procedures. For example, optimization now is executed mostly as a black box program. The analysis points provided by support codes are considered to be correct and not subject to code

sensitivities. In the preliminary design process illustrated here, the former approach clearly will not work. The new process must include a method for disciplinary engineers to examine the analysis code results as they are being generated to ensure that the optimized results are valid. When such an optimization method is available, however, I submit that the problem is far from finished. This is so because people inevitably are the designers, and the design techniques, whether through optimization or not, must take the human element into consideration.

SYSTEMS ENGINEERING - A DEFINITION

To expand on this theme, let me begin by giving you my orientation. I am in the Systems Engineering Department at Lockheed-Georgia. This gives a reasonable definition of what Systems Engineering means to us: a discipline that coordinates the engineering activities within large organizations to help produce a superior, cost-effective, timely product. By its very definition, it is a process of dealing with people in a large design operation. As such, our interest is not in the internal working of design codes, but rather in how individuals use given design codes to produce designs, and then how those individuals transmit their information to other designers in the organization.

Let me present the four main tasks of the Systems Engineering operation. They involve the management of trade studies, requirements, interfaces and technical risk. Another way to express these four tasks is Communication, Communication, Communication, Communication.

Decisions *are* the design process. By its very nature, design requires definition of some configuration from an infinity of possibilities. The best design is some compromise of many and widely varying constraints. Many times the choices to be made are aesthetic, or subjective, or not amenable to computer analysis. In these situations, and sometimes even in well-defined engineering choices, trade studies must be performed that are outside the domain of the optimization process.

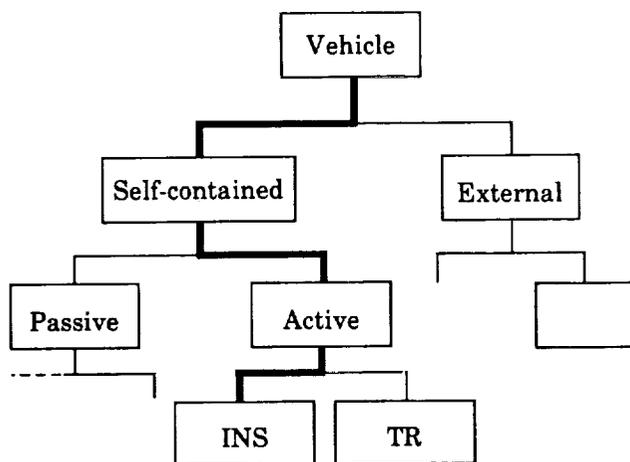


Figure 6 Hierarchy of Decisions to Select a Navigation System for an Airplane

The illustration above (Figure 6) is a simple representation of the decisions that might be made to select a navigation system for an airplane. These choices are displayed as a hierarchy, beginning with the top level vehicle considerations, and then working downward to finer levels of detail. Systems Engineering is responsible for generating such a trade tree to illustrate the decisions to be made, defining the design groups to be

involved, coordinating the studies needed, and documenting the result.

Some of the decisions illustrated in this trade tree are supported by optimized methods. For example, the vehicle may be initially sized with optimization, and components may also be designed with optimized methods. Nonetheless, when design decisions are to be made, there is a high likelihood that not all the decisions will have been supported through optimization. The point is, optimization methods are embedded in the total design process, and this must be taken into account in the development of these optimization methods.

This last feature is what I am trying to illustrate in Figure 7. Some decisions of the design process will be made within the optimization process. Some will not. But those that do not must have information available from the optimization to assist the manual decision-making process. This is true whether the outside decision is being made concurrently with the optimization or whether it lags the optimization by days, weeks or months.

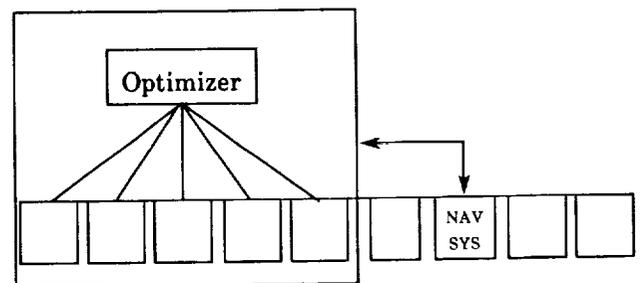


Figure 7 Trade Studies with Optimization

The implication is that information more comprehensive than just the final optimized configuration must be provided and stored. Possible information needs include sensitivities around the optimal point and the optimization history. In addition, it will be necessary to provide a way to interrupt the optimization process as it is occurring to input new information to the optimization

process and to influence, on the fly, the outcome.

REQUIREMENTS FLOWDOWN

Let me provide one more example, that of requirements flowdown. This is another example of the communication involved in the design process. In this case, the objective is to communicate to each individual designer the importance of design in meeting the top level performance requirements. This is done by analyzing the top level system requirements and assigning or allocating these top level requirements to the next lower level to determine the drivers in the system. This process is repeated to successively lower levels until the final objective is accomplished. That is, the question "What is each individual's contribution to the total system performance?" is answered at the lowest logical level.

A specific performance might be maintenance manhours per flight hour, or it might be

minimum range requirements. Whatever the requirement, this process allocates it to the lowest level of the configuration, maintains the traceability to the top level requirement and assures that the total system requirement will be met.

The question is, "What is a proper allocation?" If a top level requirement is rippled to the lowest level, which functional area should contribute what proportion to the final performance? If we rely on an optimization process that merely gives a final answer, we are blind. This is another case of not all functions being included in the optimization process. For these "outside" functions, we have no sensitivity information upon which to base realistic allocations. The actual situation might be as illustrated here, where the cost of attaining a given level of performance varies greatly from one discipline to another. I have used cost as the measure, but I could have used any measure of merit. For the illustration I have given, the

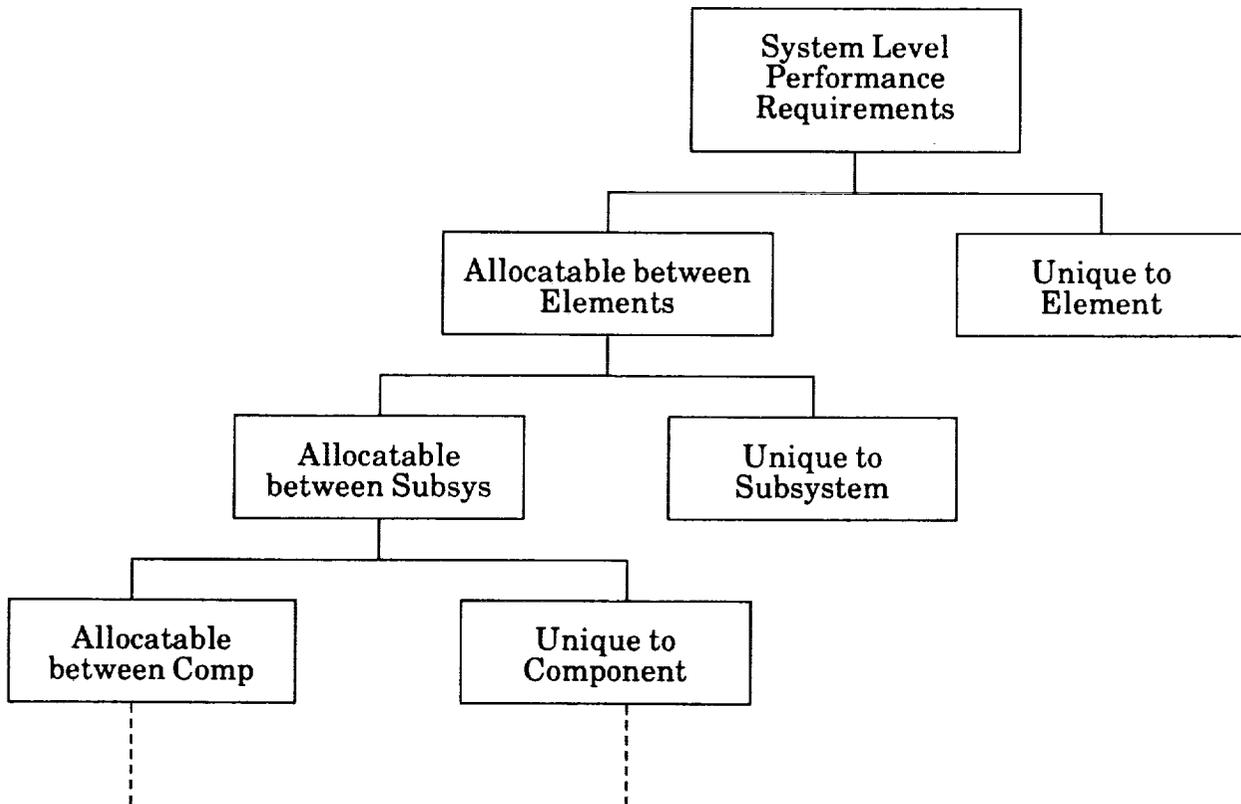


Figure 8 Requirements Flowdown

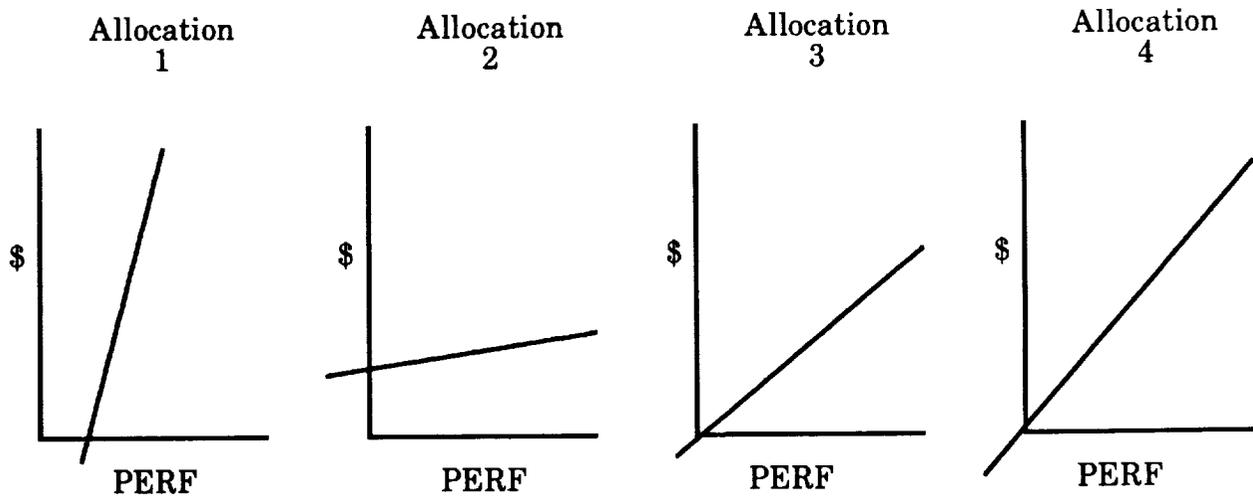


Figure 9 Optimize Allocations

optimal allocation of the requirement is that which simultaneously attains the top level system performance and minimizes the cost. In the future, our optimization processes must provide visibility for such data.

I have attempted to illustrate that optimization has a role in our design process, both today and in the future. The benefits are well known already, but I believe that we are only seeing the proverbial tip of the iceberg.

Optimization must, however, continue to be sold and this selling is best done by consistent good performance. For this good performance to occur, the future approaches must be clearly thought out so that the optimization methods solve the problems that actu-

ally occur during design. The visibility of the design process must be maintained as further developments are proposed. Careful attention must be given to the management of data in the optimization process, both for technical reasons and for administrative purposes. Finally, to satisfy program needs, provisions must be included to give data to support program decisions, and to communicate with design processes outside of the optimization process.

If we fail to adequately consider all of these needs, the future acceptance of optimization will be impeded. We simply cannot allow that to happen. Optimization is too important.

